HUMAN PERFORMANCE COGNITIVE-BEHAVIORAL MODELING: A BENEFIT FOR OCCUPATIONAL SAFETY

Brian F. Gore

San José State University, San José, CA, USA
NASA Ames Research Center, Moffett Field, CA, USA

Human Performance Modeling (HPM) is a computer-aided job analysis software methodology used to generate predictions of complex human-automation integration and system flow patterns with the goal of improving operator and system safety. The use of HPM tools has recently been increasing due to reductions in computational cost, augmentations in the tools' fidelity, and usefulness in the generated output. An examination of an Air Man-machine Integration Design and Analysis System (Air MIDAS) model evaluating complex human-automation integration currently underway at NASA Ames Research Center[1] will highlight the importance to occupational safety of considering both cognitive and physical aspects of performance when researching human error.

modeling system safety   human performance modeling,
human factors methodology   human-out-of-the-loop (HOOTL) simulations

1. JOB ANALYSIS: PHYSICAL AND COGNITIVE MODELS

Current job analysis techniques focus on the development of procedures that integrate ergonomic stresses across major body parts (e.g., lower back, upper extremities, and neck) and allow in-plant teams to rank the seriousness of exposures across different jobs. Medsker & Campion (1997) indicate that the physical themes examined in these ergonomic exposures range from job

design issues (self management, participation, task variety, significance and identity), job task interdependence, job composition (flexibility of physical procedural completion), job context (physical training, support, cooperation among members), and job process issues (physical workload, social support, member cooperation). This method of analyzing the job is often subjective in nature and relies, sometimes over-relies, on physical factors associated with task performance. This reliance of physical concerns makes the job analysis process limited in cross-domain application as many of the physical behaviors require cognitive triggering (behavioral onset). In these ergonomic programs therefore, there is little attention given to the cognitive aspects and the interaction that may occur between physical and cognitive issues. One problem with the physical approach to job design is that cognitive factors such as memory factors, memory loads, and communication between interacting individuals are often overlooked. The physical method of analyzing a job assumes that human behavior is sequential when viewed in hindsight but this orderliness is really just an artifact of the asymmetry of time (Hollnagel, 2000). This article will demonstrate a quantitative simulation technique that considers both cognitive and physical aspects of the performance of a job that may be useful for identifying job-system vulnerabilities, proposing redesigns to account for these vulnerabilities, or proposing different methods of completing the required performance. The identification and prediction of these elements within a job has a significant impact on the safety of the operator within the occupational environment.

2. HUMAN-OUT-OF-THE-LOOP (HOOTL) SIMULATIONS

Human-out-of-the-loop (HOOTL) simulation is a methodology that uses computer models of human performance to create a virtual human agent that interacts with new technologies and procedures. Many different forms of HOOTL simulations exist ranging from anthropometric human performance simulations, procedural static models, through to more complex dynamic representations of human-environment performance. These latter HOOTL simulation techniques include integrated human performance models, which use computer models to characterize a human-system environment within a computational framework. The human characteristics that are embedded within the computational framework are based on empirical research collected over the past 20 years and these interact to comprise the virtual operator. The virtual

operator is then set to interact with computer-generated representations of the operating environment over a series of repeated runs in much the same manner as testing human subjects over repeated experimental sessions. The model of human performance enables predictions of emergent behavior based on elementary perception, attention, working memory (WM), long-term memory (LTM) and decision-making models of human behaviors.   This modeling approach focuses on micro models of human performance that feed-forward and feedback to other constituent models in the human system depending on the contextual environment that surrounds the virtual operator.

HOOTL simulations can be used early in the development process of a product, system or technology to formulate procedures, and training requirements.   Also, HOOTL simulations can be used to identify system vulnerabilities where potential human-system errors are likely to arise. This will have implications for assessments of operator safety, operator productivity, and efficient system design. The use of HOOTL simulations possesses cost and efficiency advantages over waiting for the concept to be fully designed and used in practice (characteristic of human-in-the-loop, or HITL, tests). The system model development process allows the designer of the product, system, or technology to fully examine many aspects of human-system performance with new technologies.   One criticism of HOOTL tools has been that the software only predicts input-output behavior in mechanistic terms. The integrated and emergent structure of the tools however does more than solely represent input-output behavior, it attempts to prescribe how sequences of actions are planned and not simply prescribe a sequence of actions.   The framework integrates many aspects of human performance allowing each micro model component to behave in its required method, the integration of which replicates a human (Gore & Corker, 2000a). Hollnagel (2000) indicates this is critical for developing a good model.

The output measures of interest for HOOTL simulation efforts have traditionally included task demands, (mental) workload, task load, information load, attention demands, stress and procedural timing measures.   These measures have been used to identify if, when, where, and how often errors occurred within a specific job design; and combined with the load measures could be used to determine re-organized procedures to reduce time and load demands. These measures have been validated on a number of occasions across many different domains ranging from helicopter operations (Atencio, 1998), nuclear power-plant control electronic list design for emergency operations (Corker, 1994), to advanced aviation concepts (Corker, Gore, Fleming & Lane, 2000).

The recent growth in HOOTL simulation tools has focused on the study of human performance interacting with systems (Gore & Corker, 2000b) and to support prediction of future system state (Lee, 1998) with the goal of improving system and operator safety. These hybrids of continuous control, discrete control and critical decision-making models have been undertaken to represent the "internal models and cognitive function" of the human operator in complex control systems, and involve a critical coupling among humans and machines in a shifting and context-sensitive function.

3. THE MAN-MACHINE INTEGRATION DESIGN AND ANALYSIS SYSTEM (MIDAS) FAMILY OF TOOLS

The Man-machine Integration Design and Analysis System (MIDAS) Family is composed of two developmental paths. The first path is one that has focussed on the cognitive structures of complex human-system interaction and has been termed Air MIDAS. The second path has focussed on developing the visualization associated with the physical environment integrated with a slightly reduced cognitive structure and has been termed Core MIDAS. Both cognitive and physical elements of a job interact to impact performance output. A pictorial representation of one integrated and emergent HOOTL simulation tool co-developed by NASA Ames Research Center (ARC) and San Jose State University (SJSU) primarily for aviation-related occupational environments termed Air MIDAS can be found in Figure 1.

Air MIDAS is an "emergent" model of human performance – one that is based on the mechanisms that underlie and cause human behavior (Laughery & Corker, 1997). The main components of the emergent model shown in Figure 1 comprise the simulated representation of the virtual operator's world, and a symbolic operator model (SOM) that represents perceptual and cognitive activities of an agent. An important element of the SOM is the Updateable World Representation (UWR). The world representation information (environment, crew-station, vehicle, physical constraints and the terrain database) is passed through the perceptual and attention processes of the SOM to the UWR. The world information is a complex environmental representation that is created by the researcher or programmer and serves to trigger activities in the virtual operator. The UWR represents the agent's cognitive constraints on procedural completion – it contains the WM, domain knowledge, and required procedural activity structure. The UWR passes information to a scheduler within the SOM that determines the resources
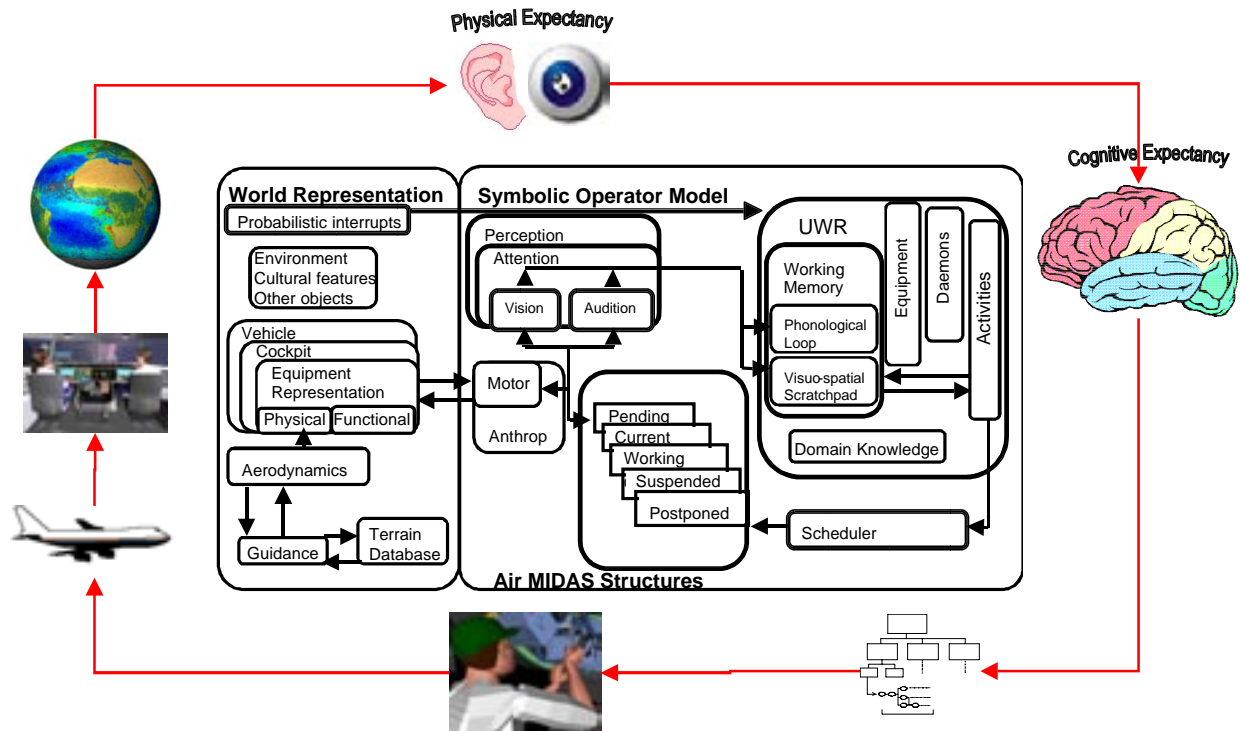
Figure 1. Air MIDAS integrated representation. *Notes:* MIDAS – Man-machine Integration Design and analysis System; *UWR* – Updateable World Representation.

available for the completion of the activity. The scheduler views WM and the measures contained within it as a capacity-limited resource. A four-channel activity loading mechanism (Visual, Auditory, Cognitive, and Psychomotor) is representative of the measures contained within WM and these activity load factors are used as constraints on the scheduling process (McCracken & Aldrich, 1984). The scheduler controls the flow of UWR into and out of WM based on its knowledge of activities to be performed, ensuring that the number of nodes in WM at any given time does not exceed the WM node capacity (with the exception of daemon-introduced nodes into WM). This cognitive structure interacts with physical constraints on an virtual operator's performance.

The visualization component of the MIDAS software developed by the Army and NASA ARC in Figure 2 exemplifies the cognitive and physical visualization of the linkage and is termed Core MIDAS. This graphic demonstrates an anthropometric figure (EDS' JACK™) interacting with an environment (top left), a view from the figure's eyes (top right), six-channel workload (lower left) and situation awareness (lower right). Core MIDAS demonstrates the visualization of the physical and cognitive worlds in a computer-aided fashion and alludes to the potential interaction of the physical and cognitive components of jobs when

developing design guidelines to maximize system and operator safety. These physical and cognitive factors are also critical components when verifying that the software is performing in the programmed manner – i.e. designed to represent the human operator completing complex or demanding behaviors.
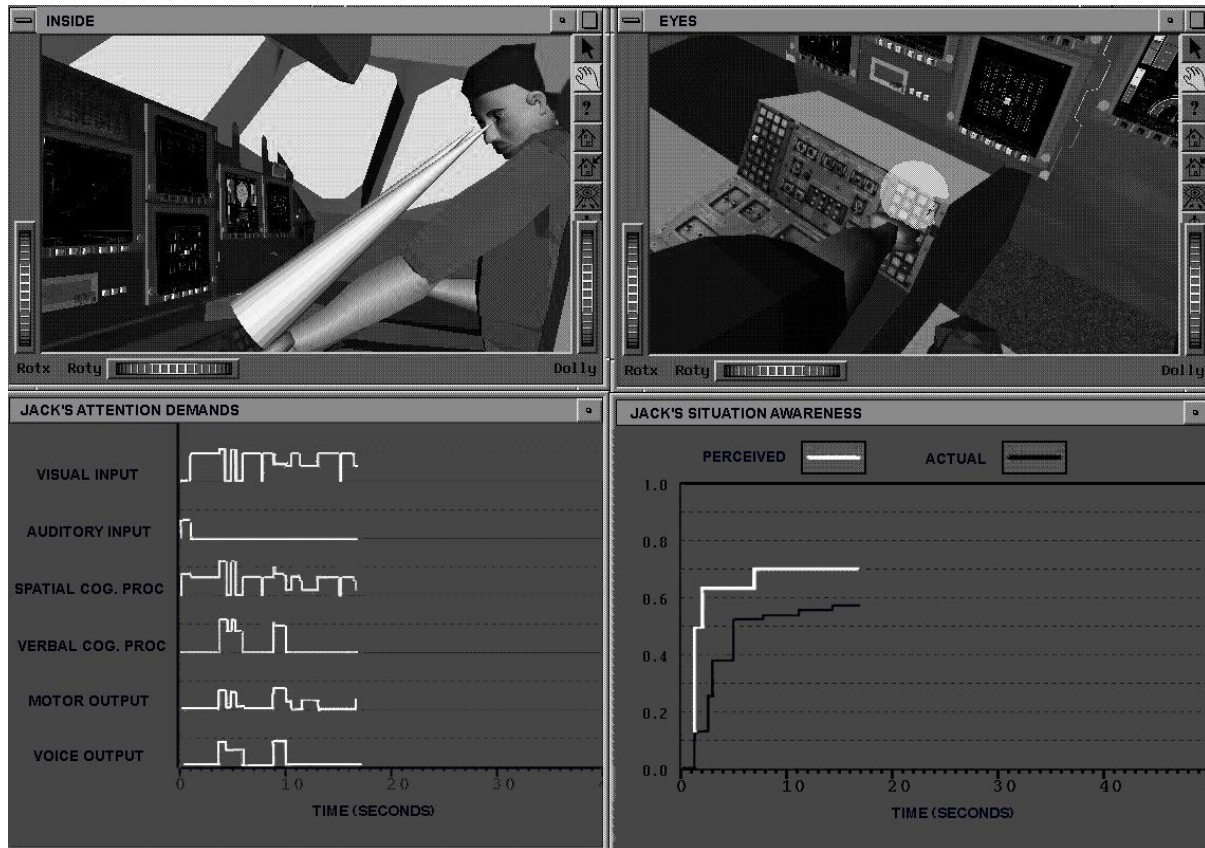

Figure 2. Core MIDAS' visualization of the occupational environment. *Notes.* MIDAS – Man-machine Integration Design and Analysis System.

Air and Core MIDAS both use a procedurally-based language that invoke a series of predetermined goal-oriented behaviors. The environment triggers activities (procedures) within the virtual operator and the virtual operator completes the desired procedure in accordance with their resource availability, their goals and their priorities. Air MIDAS is exercised in a multiple-run operating mode (termed Monte Carlo simulation). In this mode, each run constitutes a scenario run. The loading factors on the operator vary over time from run to run depending on the stochastic variations in each virtual operator's behavior and stochastic elements in the environment. The result is that each run is unique and varies around these elements, which results in a distribution

of performance times and potential differences in the quality of the simulated operators' performance.   The scheduler invokes rules to determine the triggering of procedures. Procedures can be postponed, suspended, working, current, or pending. In turn the SOM selects activities to perform, some of which interact with the representation of equipment in the simulated world and change the behavior of the relevant part of the system. This series of actions and interactions among the structures within the HOOTL software is key when attempting to model perceptions and interpretation (characteristics of human cognition) of information from the world state. These perceptions and interpretations impact the physical performance of a task because without perception and interpretation of the external environment, there cannot be an accurate response of the virtual operator.

4. HUMAN PERFORMANCE, HUMAN ERROR AND CONTEXTUAL EFFECTS

Technological increases in the human-system integration environment are often accompanied by increases in a reliance on human cognitive abilities for successful performance and these higher cognitive processes are characterized by higher error rates (Hollnagel, 1993; Reason, 1990). Given this relationship, it is being proposed that the use of cognitive modeling tools that possess validated memory representations will be useful in pinpointing vulnerable areas that are environmentally associated (contextual manipulations). The vulnerable areas can then be addressed through training procedures and various other job re-design processes once the error prone segment of the job has been identified.

Reason (1990) defines human error as being the failure of planned actions to achieve their desired output. Reason indicates that failures can occur in one of two ways. The action may conform to the plan but the plan is inappropriate for achieving the desired goals, a failure at the planning stage; or the plan is adequate but the actions deviate from the plan, a failure of execution. Reason indicates that errors can be reduced or eliminated by improving information sources within the workplace. In Reason's classification, errors are attributed as being either active human failures or latent human failures. Active human failures are failures that are committed by those in direct contact with a system. Latent failures are loopholes in the system's defenses and are points in the system where the potential for human error has existed for some time and emerge when the vulnerability and the operator's performance align.

Explanations for the latent error classification surrounds skill-based, rule-based and knowledge-based performance. The physical world is one that is characterized by skill-based mechanisms guiding the completion of performance on a task whereas the cognitive world is one that is characterized by knowledge-based mechanisms. Skill-based mechanisms are those mechanisms that are associated with routine, highly practiced tasks while the knowledge-based mechanisms are those that are characteristic of novel, difficult or dangerous tasks (Reason, 1990). Reason's human error concept is organizationally defined but has its etiology in identifying the root causes of human error that are associated at an individual level.

Hollnagel (1993) further refines this definition of human error to one that is specifically aimed at predicting human error in cognition. He indicates that cognitive errors can be viewed according to how they account for the underlying causes of actions. Hollnagel indicates that erroneous behavior can be viewed as resulting from sequential or procedural errors or contextual factors. The procedural model of cognition is a normative model indicating how a task should be carried out. Any deviation to this plan results in an error. The contextual control model of cognition concentrates on how the control action selection occurs, rather than focussing on the adequacy of the sequences of actions for attaining the goal.

To date, HOOTL researchers have paid little attention to the environment's impact on the behavioral predictions generated by their cognitive models and the link between the behaviors and the cognitive processes required by a given situation. One theory that attempts to provide such a link is Hollnagel's (1993) contextual control model (CoCoM) through its cognitive processing module. CoCoM states that a person's comprehension and action depends on how a context is perceived and interpreted. The purpose of the cognitive processing module within CoCoM is to meet a particular goal. This goal is satisfied by actively referring to the environment, to knowledge, or to cognitive processes as opposed to passively responding to the environment. WM plays into this process by storing contexts, which, in turn, trigger relevant answers. These WM modules are sequenced by WM storage. CoCoM views human performance as determined, for the most part, by the context that characterizes the environment of the human operator and the performance of the individual operator occurs as a result of the active planning ongoing by the individual operator in response to the environment. Hollnagel, consistent with Reason (1990), proposes that the actions that are carried out by the human can fail to achieve their goal as a result of accurate performance according to an inadequate plan (cognitive planning error) or deficient performance (physical

error) in carrying out a successful plan. Hollnagel argues that research surrounding human error appears to confuse the causes of the events surrounding human error with the internal psychological processes or cognitive mechanisms that are presumed to explain the action (cause of event versus class of actions). CoCoM, represented in Figure 3, outlines the inter-relationship among human internal cognitive mechanisms and control levels on behavioral outcomes. The dynamics of these mechanisms demonstrate the impact that context has on the performance of the individual in the environment rather than by an inherent relation between actions and demonstrate that the CoCoM can be computationally applied, thus the reason for its inclusion here.
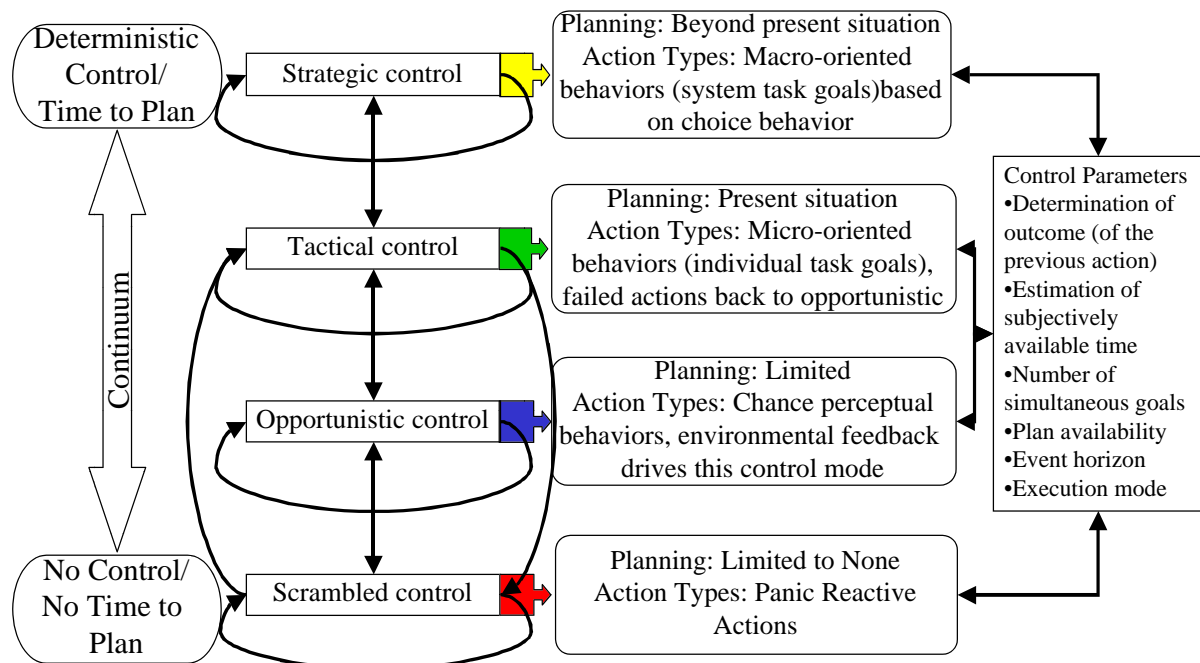

Figure 3. Representation of Hollnagel's contextual control model.

5. HUMAN PERFORMANCE MODELING
ERROR STRUCTURES

HOOTL methodologies in general, and Human Performance Models (HPM) in specific, possess the capability to represent many error classes. The mechanisms that characterize the HPM allow for the incorporation of logic to

represent errors through various embedded computational structures. Two examples of error classes that can emerge from the Air MIDAS model, UWR errors (mismatch) and memory errors, will be explained. These error classes are characteristic of human performance in complex systems and of multi-crew behavior, and they represent a potential for incorporating the dynamic CoCoM of error behavior. These error classes also demonstrate unique aspects of the Air MIDAS software.

The Updateable World Representation (UWR) error is one class of error that emerges based on misunderstanding or mishearing among virtual operators in the simulation. The misunderstanding among the virtual operators is representative of a mismatch between the cognitive structures of the operator's understanding of the environment. The contextual error emerges when one virtual operator erroneously "thinks" a different virtual operator had received shared information and carried out behaviors in accordance with this belief. The UWR errors manifest themselves as increases in workload, response delays to currently ongoing tasks, and in increases in time to complete a procedure. UWR errors are also demonstrated in communication and negotiation increases between all virtual operators. The error vulnerability arises because of informational differences provided to the operators and subsequent increases in time to complete a series of actions occurs due to cognitive negotiation tactics that occur between agent in the simulation necessary to arrive at a consistent worldview. UWR examination therefore can be particularly important in multi-operator interactive environments.

The potential for UWR errors can be tested in various environments to measure worker productivity and safety, and determine whether procedural changes are predicted to have a positive effect on operator performance. If HOOTL simulations are used to determine where, when, and why errors are likely to occur, suggestions on training and procedural optimizations to minimize the occurrence of the error can be suggested and tested.

Memory errors are occurrences of memory lapses in the cognitive structure of the virtual operator that can occur as a result of excessive time to complete procedures or because of resource competition for the limited capacity store of the virtual operator's cognitive structure. This resource competition impacts the successful performance of the ongoing procedure that the virtual operator is performing. Gore and Corker (2002) found that virtual operators were faced with situations that exceeded the limited capacity memory store of the virtual operator. Exceeding the limited capacity store of the virtual operator impacted the performance of the surface operations that they modeled. Memory errors emerged from Air MIDAS when virtual operators omitted or substituted parts of

a required procedure, or when the scheduler became invoked and procedures were "scheduled" or "failed". In the face of not having the required information, virtual operators engaged in non-optimal performance and occasionally completed incorrect physical procedures for the context within which the virtual operator was performing. Procedural interruptions occurred when operators were faced with procedures that competed for declarative memory resources. These resources decayed across time and were not accessible if time extended beyond an acceptable upper time boundary (decremented by the STM decay rate on each tick of the Air MIDAS simulation which then gets combined with the LTM store). When the activation level fell below a retrievability threshold, the node attribute values became unretrievable and procedures failed. High workload conditions were predicted to elicit the error. The memory errors manifested themselves as differences in memory load, memory onset and finish times, dropped tasks, ongoing procedures and procedural interruption, visual workload increases, and differences in workload patterns.

A second manner in which memory errors emerged was in the scheduling of upcoming procedures. Gore and Corker (2002) found that tasks and procedures invoked the scheduling mechanism when there were a number of items occupying the memory store. One item in memory was shifted out of the limited capacity store by subsequent information entering the virtual operator's cognitive store. The information provided to the respective virtual operator was lost from the "active" list, or the series of active procedures scheduled to occur, if it was not written down. Given that the human operator is characterized as a limited capacity store, items within this memory structure fall out of memory if not rehearsed. Rehearsal occurred by mentally recalling the required information bits, or when this was not available relying on some external visual aid like a list. The virtual operator was programmed to consult a list (notation of directions) in conditions where they lost information from within their cognitive store. The memory errors manifested themselves as differences in dropped tasks, procedural interruption, and differences in workload patterns.

A similarity exists between the aviation and the occupational safety fields. Both fields are attempting to integrate new technologies with current procedures in an effort to increase productivity while maintaining safety in the operational environment. The new technologies often incorporate some form of automation to assist the operator complete their job safely and productively. This automation often relies heavily on an operator's memory and therefore contains similar vulnerable system elements as those in the aeronautic community. The potential for these memory errors to emerge can be tested in occupational environments to measure worker task and procedural completion,

and examine the effect that various performance modifiers (e.g. automation, training, re-design) has on assisting the successful performance of a job requirement. Many options exist to assist an operator's memory when the operator is completing complex tasks – electronic checklists, placement of equipment, cross checks with other operators in the operating environment, or other automated reminding mechanisms. The pattern associated with the output from the HOOTL simulation can be used in developing memory aids for operators, or can be used to decide on implementing various other job re-design strategies such as cognitive rehearsal, or repetition to account for system vulnerabilities. System vulnerabilities in the occupational environment can therefore be successfully modeled and procedural re-design or job re-design performance can be examined through the use of the HOOTL human performance model to predict the effect the re-design may have on operator performance (increased efficiency and increased safety). The HOOTL prediction can provide valuable insight earlier and more efficiently (in terms of time and costs) into specific job related demands and the effect that procedural changes will have on job completion.

6. CONCLUSION

Understanding the mechanisms that underlie human error when operators are completing procedures in complex systems alludes to an understanding of the underlying structures that interact to form emergent human behavior. This article demonstrates the recent advances in computational cognitive modeling tools, specifically dynamic models of human performance and human error. A critical aspect of the methodology is the interaction that exists among the physical and cognitive structures in completing complex jobs. The identification of mechanisms involved in the creation of error will certainly lead to a better understanding of the concepts associated with safety underlying human performance, and will lead to more solid computational predictive tools of human performance, especially in the increasingly complex and automated work environment. The computational analysis methodology permits a closer link between the job, the use of the automation and the human performer complete with the human's physical and cognitive abilities. The coupling between the job, the use of the automation and the human is critical if the tools that are being generated today will be useful in accomplishing the ultimate goal of accurately predicting human performance in the increasingly complex, and cognitively demanding work domain.

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